How to control input ripple and noise in buck converters

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Today's feature-laden portable electronics devices, typically running off a single Lithium-ion cell, often use one or more step-down DC/DC converters to power the core processor or other key functions. These fast transient, compact, power management ICs offer significantly higher efficiency than comparable linear alternatives. Moreover, as portable system designers have grappled with rapidly shrinking product footprints, power semiconductor designers have migrated to step-down converters using higher and higher switching frequencies to allow designers to take advantage of smaller external inductors and ceramic capacitors.

The move to step-down converters using higher switching frequencies has generated another problem for system designers however. If it isn't filtered, DC/DC converter input ripple and noise can reach levels high enough to interfere with other devices powered from the same source. Fortunately, a number of relatively simple methods are available to reduce input noise and its impact on other devices. This article will describe these sources of input noise and ripple and some basic methods to attenuate its occurrence.

Two noise sources

Input noise in a step-down DC/DC converter has two components. The first occurs at the fundamental switching frequency commonly referred to as ripple. The second noise component is associated with the very high frequency ringing that occurs during switching transitions. Figure 1 below shows a typical input ripple and noise waveform for a buck converter with both the saw-tooth ripple and high frequency ringing components.

The best method to use to reduce input noise depends on which noise component requires filtering. To properly analyse input noise, a designer must first examine these components separately.

The output inductor of every buck converter connects to the input during the on portion of the switching cycle and then disconnects during off periods. The battery and output inductor current are constant throughout the switching cycle while the input capacitor has no DC component. To supply a constant DC voltage on the input, the input capacitor charge (It) at Ton must be equal and opposite the capacitor charge at Toff .

The input capacitor wave shapes are illustrated in Figure 3. Equation 1 explains the saw-tooth characteristics of the input voltage ripple.

Ripple magnitude varies with input voltage and reaches a maximum at 50 per cent of the duty cycle. Designers can reduce input ripple by either boosting the capacitance or reducing the equivalent series resistance (ESR) of Cin. Ceramic capacitors typically exhibit a very low ESR and add little to the input voltage ripple. The equivalent circuits for a buck converter for both Tonand Toffportions of the switching cycle are depicted in Figure 2.

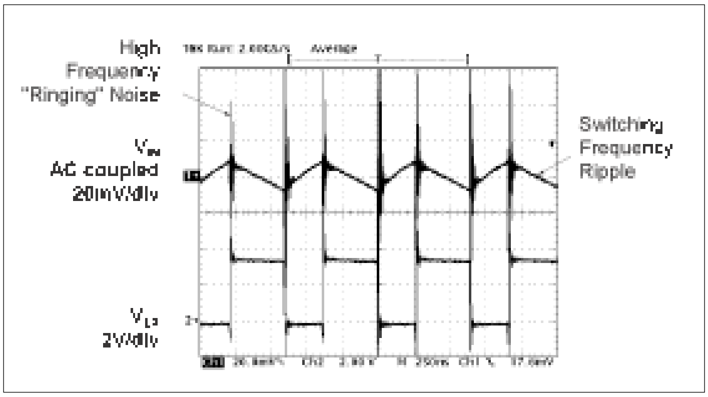

Figure 1: Typical Input Ripple and Noise Waveform for Buck Converter

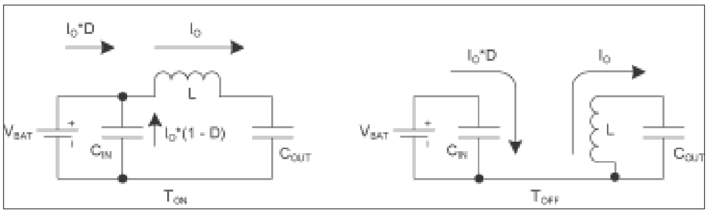

Figure 2: Equivalent Circuits for Buck Converter for Ton and Toff portions of switching cycle

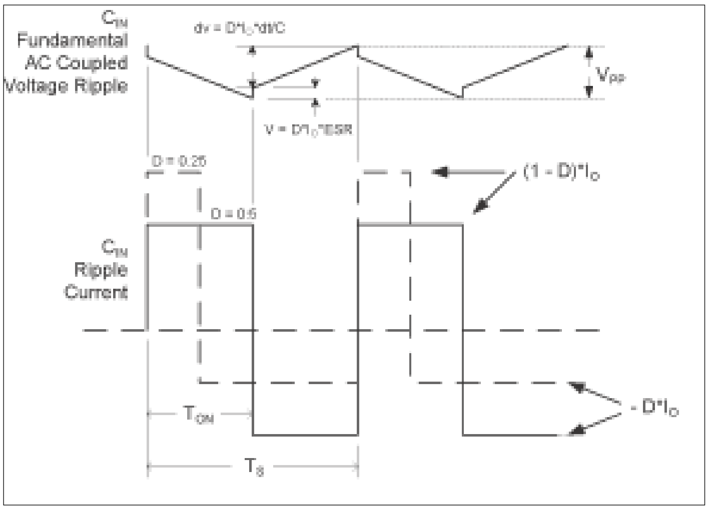

Figure 3: Input Capacitor Wave Shapes

High frequency noise

In most portable applications, high frequency input noise in DC/DC converters is a product of high frequency ringing or oscillation associated with parasitic elements of the converter power stage and typically runs above 100 MHz. Energy stored in the inductive and capacitive parasitic elements oscillates or rings during the switching transitions. Ringing at the edges of the switching waveform repeats itself at each cycle. Since the ringing frequency is very high, a typical bypass capacitor alone is ineffective in attenuating this noise. Figure 4 below illustrates this fact. The graph shows the impedance vs. frequency characteristics of a typical ceramic capacitor. Impedance above 100 MHz is inductive and similar regardless of capacitor size or value. Obviously adding a smaller ceramic capacitor in parallel to the larger "bulk" input capacitor would not reduce this high frequency noise significantly.

Since the ceramic capacitor looks inductive in the frequency band in which this noise occurs, designers must add a series element for attenuation. This additional element could be as

$$V_{PP} = D \cdot I_O \cdot \left(ESR + \frac{(1 - D)}{C_{IN} \cdot F_S} \right)$$

$$= \frac{V_O}{V_{IN}} \cdot I_O \cdot \left(ESR + \frac{1 - \left(\frac{V_O}{V_{IN}}\right)}{C_{IN} \cdot F_S} \right)$$

$$= V_{PP} = \frac{1.8V}{3.6V} \cdot 0.4A \cdot \left(0.002\Omega + \frac{1 - \left(\frac{1.8V}{3.6V}\right)}{4.2\mu F \cdot 1.4MHz} \right)$$

$$= 17.4mVpp$$

$$D = \frac{V_O}{V_{IN}}$$

Equation 1

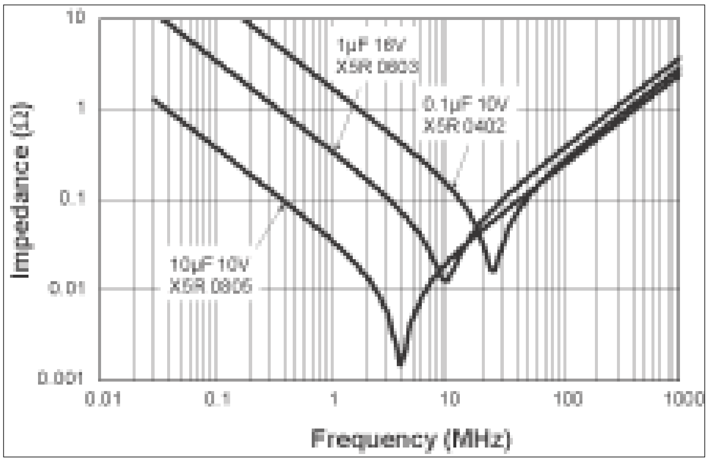

Figure 4: Bypass Capacitor Ineffective In Attenuating High-Frequency Noise

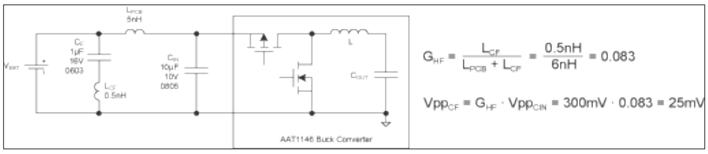

Figure 5: Equivalent Circuit is Inductive Divider

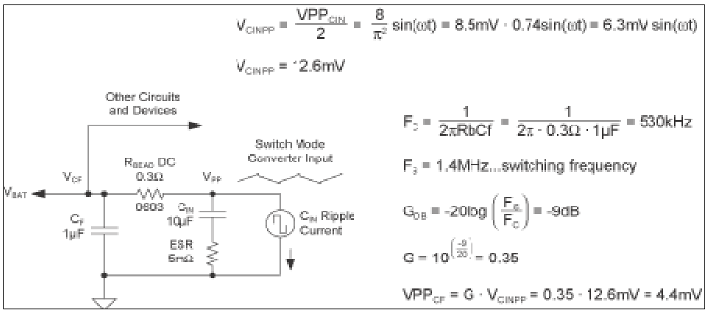

Figure 6: Improved Frequency Rejection Example Circuit

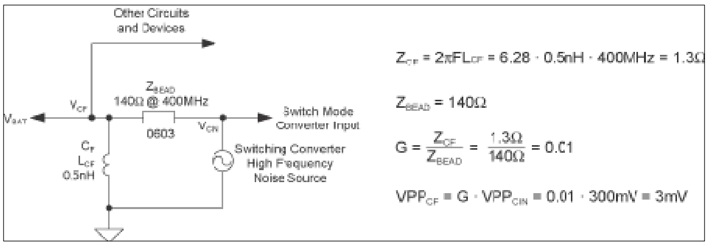

Figure 7: Network for Estimating Attenuation

simple as the impedance of the PCB trace feeding the additional device powered by the common source. The equivalent circuit is an inductive divider (see Figure 5). The typical impedance for a 50 mil wide trace of 2 ounce copper on 62 mil FR4 board is about 11 nH per inch or about 5.5 nH for a half inch long trace.

The inductance of a typical 1µF 0603 ceramic capacitor is about 0.5 nH. This corresponds to 21 dB or 1/12x reduction in the high frequency input noise above 100 MHz. When additional attenuation is needed, designers can use a series resistor which provides an L/R network whose attenuation can be determined at the noise frequency or a ferrite bead which increases the high frequency series impedance while reducing DC losses.

Using ferrite beads to attenuate noise

In some cases the impedance of the circuit board trace is insufficient as a series element for the low pass noise filter. Designers can increase the series impedance with a small surface-mount ferrite bead to improve noise rejection.

The DC resistance of the ferrite bead and the filter capacitance (Cf) can be used to determine the corner frequency and the corresponding ripple attenuation at the switching frequency. To estimate the ripple attenuation with a ferrite bead, approximate the input ripple waveform as a saw-tooth and reduce it to its fundamental frequency component. As an example compare Figure 6 below with Figure 1 presented earlier. In Figure 1 the measured level of the peak-to-peak saw-tooth ripple is about 16 mV while the calculated ripple from equation 1 is about 17 mV. Figure 6 shows an example circuit and calculation for the improved frequency rejection with a ferrite bead.

To understand the high frequency attenuation, the designer must examine the ferrite bead impedance at the resonant frequency of the high frequency noise seen at the input. In Figure 7 the high frequency noise is visible at about 400 MHz. Figure 8 indicates that the 400 MHz impedance of the ferrite bead is approximately 140Ω. Figure 4 shows that the corresponding impedance of the filter capacitor at 400 MHz is about 1&Omega and is inductive. One can estimate the attenuation at 400 MHz using the network show below in Figure 7.

The impedance characteristics of a typical surface mount ferrite bead are illustrated in Figure 8 below. The ferrite bead has a small DC resistance which enables it to pass the DC current with minimal effect on system efficiency. It also has large impedance in the frequency band where the converter high frequency noise occurs. The graph below indicates that the impedance above 200 MHz exceeds 100&Omega. This example uses a ferrite bead with a 500mA DC current rating and a DC resistance of 0.3&Omega that helps minimise losses associated with adding a series element.

Measurement considerations

Figure 9 below illustrates typical input noise waveforms for a model AAT1146 fast transient, step-down converter manufactured by AnalogicTech with an input filter formed by the input trace inductance and a 1 µF ceramic capacitor. In the expanded views one can see that the resonant frequency of the parasitic elements occurs at about 400 MHz. Given that this component of the input ripple occurs at such a high frequency, a designer cannot employ a typical connection of the scope probe to some arbitrary location on the printed circuit board for an accurate measurement.

The best way to ensure an accurate measurement is to use the “ring and tip” scope probe method with a 50Ω termination at the scope. With this method

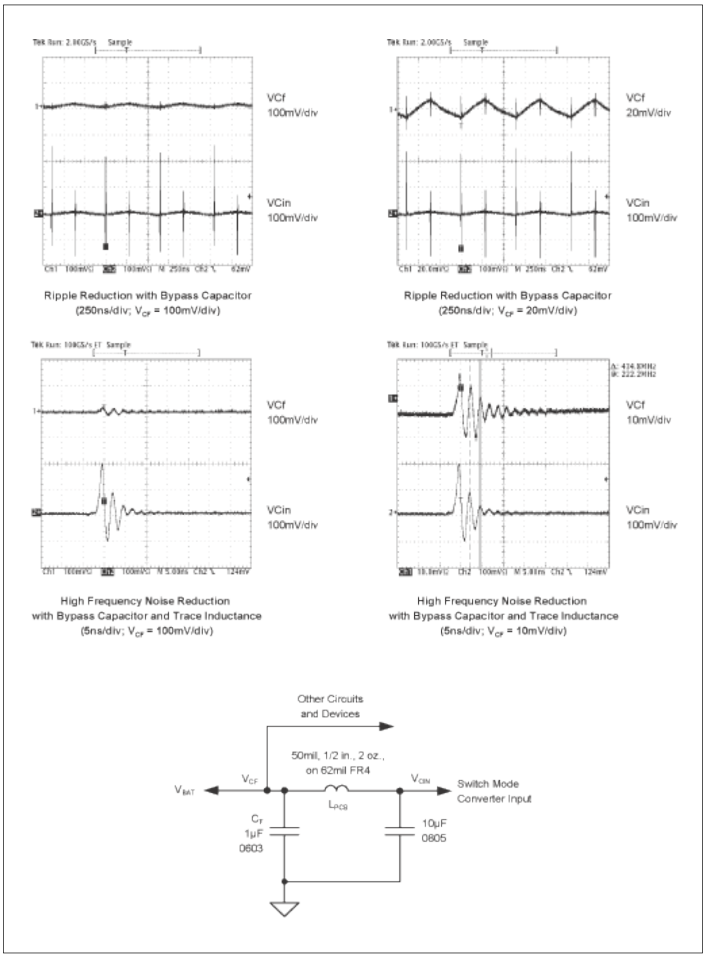

Figure 9: Typical Input Noise Waveform

the scope probe plastic sheath is removed in order to expose the ground at the tip of the probe.

This test methodology provides a very short connection from the probe ground to the return side

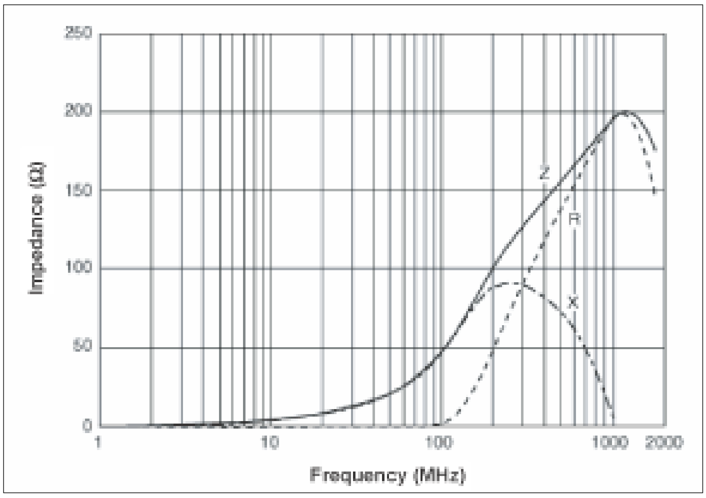

Figure 8: Typical Impedance Characteristics of Surface Mount Ferrite Bead

of the capacitor and thereby eliminates radiated pickup and delivers a more accurate measurement of the conducted ripple and noise.

Conclusion

Using ever-higher switching frequencies, the latest generation of step-down DC/DC converters offer portable system designers a high efficiency power source in a small footprint and capable of operating with extremely small external components. But when these converters share a common input voltage with other devices, the noise generated by the converter can generate dangerous levels of interference. By using simple filtering techniques such as a ceramic bypass capacitor or , when needed, a ferrite bead placed between the converter input and other devices powered from the same source, designers can successfully attenuate this noise and improve system performance.